

Estimating Ordnance Penetration into Earth

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ABSTRACT

USAESCH is currently engaged in projects which require detection and removal of buried ordnance. It is desirable to have an estimate of the expected depth of the ordnance.

Several methods for estimating the penetration of ordnance into earth have been investigated. Each method has distinct advantages and disadvantages. Methods are compared for required detail of input information, time required for calculation and resulting depths.

Comparison of these methods shows that one method is preferable. This method, based on an equation from TM 5-855-1 dated November 1986 [1], is outlined and an example is discussed.

A database of recovery depths from at least 13 project sites has been compiled. Actual recovery depths are compared to estimated penetration depths.

INTRODUCTION

The USAESCH is currently engaged in projects which require detection and removal of buried ordnance. It is desirable to have an estimate of the expected depth of the ordnance. This expected depth is required as part of the site specific analysis required by paragraph C.4.c. of Chapter 12 of DoD 6055.9-STD, "DoD Ammunition and Explosives Safety Standards" [2].

Several methods for estimating the penetration of ordnance into earth have been investigated. Each method has distinct advantages and disadvantages. Methods are compared for required detail of input information, time required for calculation and resulting depths.

First, an equation developed by the U.S. Army Engineering Waterways Experiment Station (WES) for determining fragment penetration into earth is evaluated. In this analysis, the fragment is assumed to be a complete ordnance item. The munition information that is required to use the WES equation is the weight of the ordnance item and the striking velocity of the ordnance item. Since the striking velocity depends on many variables (charge used, firing angle, and distance traveled), a maximum velocity is assumed. Conservatively, the velocity will not exceed the muzzle velocity with the maximum charge.

As a check of the WES equation, the penetration of several munitions into sand have been determined using a hydrocode analysis. The results using the HULL hydrocode [3] have been compared to the results using the WES equation.

PENCRV3D [4], computer software developed at WES, was evaluated as a means of predicting ordnance ground penetration depths. This evaluation is discussed in depth in “Evaluation of PENCRV3D for Determination of Ordnance Ground Penetration” by Douglas Grant and Michelle Crull [5]. The results of this analysis are compared to the results of the WES equation and the hydrocode analysis.

Finally, results from a database of actual recovery depths are compared to the results of the previous computations. A complete discussion of this database is given in “Ordnance and Explosives Recovery Depth” by Jason Adams [6].

PENETRATION ANALYSIS

U.S. ARMY ENGINEERING WATERWAYS EXPERIMENT STATION (WES) EQUATION

An equation developed by WES provided fragment penetration prediction for soils ranging from clay to dry sand. This equation is provided in TM 5-855-1 dated November 1986 [1]. For the purpose of ordnance penetration analysis, the fragment is assumed to be the ordnance item. The striking velocity of the ordnance item is dependent on the propellant charge used in firing the item, the firing angle and the distance traveled. Since these factors are generally unknown on an ordnance and explosives (OE) site, a conservative value of the muzzle velocity at the maximum charge is used. The ordnance is assumed to strike normal to the ground surface.

The equation is given as:

$$t_p = 1.975W_f^{(1/3)}k_p \log\left(1 + 4.65\left(\frac{V_s}{10^3}\right)^2\right)$$

where t_p = penetration depth (in)
 W_f = fragment weight (oz)
 k_p = constant depending on soil type (see Table 1)
 V_s = striking velocity (feet per second)

Table 1: Soil Penetration Constants

Soil Type	$k_p(\text{in/oz}^{1/3})$
Limestone	0.775
Sandy Soil	5.29
Soil Containing Vegetation	6.95
Clay Soil	10.6

Several ordnance items that have been found on various OE sites have been used to evaluate the WES equation. These items with their weight and muzzle velocity are listed in Table 2.

Table 2: Ordnance Weight and Velocity

Ordnance Item	Weight (lb)	Muzzle Velocity (ft/sec)
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155 mm M107	96.75	2244
105 mm M1	33.95	1550 (charge 7)
75 mm M48	14.6	1250
40 mm M822	5.5	1100
37 mm M63	1.61	2650
2.36" Rocket	3.4	265

The resulting depths of penetration using the WES equation are shown in Table 3.

Table 3: Depths of Penetration of Ordnance into Soil

Ordnance Item	Depth of Penetration (ft)			
	Limestone	Sand	Soil Containing Vegetation	Clay
155 mm M107	2.0	14.0	18.4	28.0
105 mm M1	1.1	7.7	10.1	15.4
75 mm M48	0.7	4.9	6.5	9.9
40 mm M822	0.5	3.2	4.2	6.4
37 mm M63	0.6	3.9	5.2	7.9
2.36" Rocket	0.1	0.4	0.5	0.8

HYDROCODE ANALYSIS

The HULL hydrocode [3] was originally designed and coded by R.E. Durrett and D.A. Matuska in 1972 at the Air Force Weapons Laboratory (AFWL) for simulation of nuclear weapons effects. The OTI*HULL code is currently being maintained by Dan Matuska, John Osborne and Ned Piburn of Orlando Technology, Inc. of Shalimar, Florida. HULL is a system of programs that solves two and three dimensional, multi-material, multi-phase dynamic continuum mechanics problems in Eulerian and/or Lagrangian frameworks. In the HULL hydrocode, continuum mechanics equations describe the behavior of continuous media by applying the principles of conservation of mass, momentum and energy from a macroscopic point of view. An equation of state is employed to relate pressure, density and internal energy. In addition, a constitutive equation describes the relationship between stress and strain, work hardening and thermal softening. The conservation equations, being non-linear, coupled, partial differential equations with no closed form solution, must be solved numerically.

The first stage in the numerical solution is to discretize the region of solution. This is done by creating a mesh of points in the solution region and expressing the spatial and temporal derivatives in the governing equations as finite difference algorithms. By doing this, the set of governing partial differential equations becomes a set of algebraic equations that are solved for each value of time throughout the computational mesh. Results from this analysis can be plotted as material "moves" through the mesh as a function of time.

Hydrocode calculations can provide a good deal of insight and detailed information about the physical processes which are occurring during high-speed impacts. The ability to trace the time history of various points of interest and to plot snapshots of the impact at various time intervals

allows one to perform the most highly “instrumented” test possible at a fraction of the cost of conventional testing.

The depth of penetration into sand of the six ordnance items listed in Table 2 was calculated using the HULL hydrocode. In order to perform the hydrocode analysis, the geometry, weight and striking velocity of the ordnance item must be defined. Also the equations of state of the ordnance case and the soil must be defined. As a conservative estimate, the ordnance was assumed to strike normal to the ground surface. The variation in velocity with time and the depth of penetration with time for the 155 mm, the 105 mm, the 75 mm, the 40 mm, and the 37 mm are shown in Figures 1 through 5, respectively. The results from the hydrocode analysis are listed in Table 4.

Table 4: Penetration Depths in Sand Using Hydrocode Analysis

Ordnance Item	Depth using Hydrocode Analysis (ft)
155 mm M107	16.8
105 mm M1	9.4
75 mm M48	5.7
40 mm M822	2.9
37 mm M63	4.1
2.36” Rocket	0.46

PENCRV3D ANALYSIS

PENCRV3D [4] is a computer program developed for predicting projectile penetration into curvilinear geologic/structural targets. The program was developed under the hardened structures research program at WES. PENCRV3D predicts the trajectory and other response characteristics such as the yaw, pitch, and roll angles and their respective rates of change in three dimensional (3D) space as a function of time. The program uses a differential area force law (DAFL) formulation to solve the six equations used in describing the 3D motion. Using this method, the projectile is divided into a finite number of differential rectangular elements. The resulting stress on each element is calculated and applied at the center of the area of the element at a series of discrete time steps. Element discretization is user-definable through the input deck as is the target definition. PENCRV3D also allows the definition of multiple target layers in the model definition. Particularly attractive is the fact that the model has been validated using actual test data.

Use of PENCRV3D requires the definition of the ordnance geometry (shape, length, thicknesses, diameters, etc.), the striking angle, and the striking velocity as well as the soil parameters. A study has been completed to determine the sensitivity of the PENCRV3D model to variations in the ordnance center of gravity, striking angle, striking velocity and target soil type. The 155 mm M107 projectile was used for this study.

For comparison with the other methods discussed, the geometric model of 155 mm M107 projectile that is included in the PENCRV3D user’s manual was used. This model has the center of gravity located at 18.299 inches from the nose tip. A striking angle of 30 degrees from

horizontal and a striking velocity of 705 feet per second were used. PENCVR3D has a database of soil definitions varying numerically from 2 for well-cemented sand to 50 for wet clay. A soil index number of 5 was used for medium dense, medium or coarse sand. The maximum depth of penetration calculated using PENCVR3D for this model is 3 feet.

ORDNANCE AND EXPLOSIVES RECOVERY DEPTH DATABASE

USAESCH has developed a database of recovered OE items from Formerly Used Defense Sites (FUDS) and Base Realignment and Closure (BRAC) projects. Information on the identification of the item, the actual map coordinates at which it was found, and the actual depth to the top of the item is collected for each OE item recovered. All information collected has been compiled into a database. Four of the categories that can be used to sort information are OE category (projectile, rocket, bomb, etc.), OE item identification, recovery depth in inches, and status of OE item (fired or buried).

The ordnance and explosives recovery depth database contains the information from more than 13 project sites. Information from all recovered OE items is entered into the database. This information includes whether the item was fired or buried, a description of the item, the recovery depth and the soil type. Soil type was added to the list of information required after the database was started so this information is not available for all items. Only fired items are considered for the purposes of this discussion. For the munitions considered the information in Table 5 is available.

When looking at the recovery depth information in Table 5, it should be noted that these are the depths at which the items were recovered. This is not necessarily the penetration depth. These depths may have been influenced by several factors including cut or fill of the soil in the area, frost heave, or tilling for agricultural purposes.

Table 5: Ordnance and Explosives Recovery Depth Database Information

Ordnance Item	Number of Items in Database	Soil Type	Range of Recovery Depths (ft)
155 mm M116 Smoke	23	Sand	0.3 – 3.0
155 mm M107 HE	1	Sand	2.0
105 mm M1 HE	2	Not Available	0 – 0.5
105 mm M84 Smoke	17	Sand	0.5 – 3.2
105 mm M314 Illum	5	Sand	1.1 – 3.0
75 mm AP-T	2	Loam	0.3 – 0.7
75 mm AP-T	4	Silty Sand & Clay	0.5 – 4.0

75 mm French Mk IV	5	Sand	0
75 mm M48	2	Loam	0 – 0.7
75 mm M48	5	Not Available	0.1 – 1.0
75 mm M48	3	Sand	0 – 1.2
75 mm M309A1	7	Sand	0.5 – 2.0
75 mm Practice	5	Not Available	0.3 – 1.0
75 mm Shrapnel Mk I	58	Sand	0 – 2.5
2.36" Rocket	18	Alluvium, Sand, Clay & Silt	0 – 0.5
2.36" Rocket	2173	Silty Sand & Clay	0 – 1.5
2.36" Rocket	75	Sand	0 – 4.0

COMPARISON OF DEPTHS

Since the hydrocode analysis is based on first principles of physics, these depths will be used as the baseline to which the other analytical depths will be compared. Table 6 shows the comparison between the depths of penetration into sand calculated using the hydrocode analysis and the WES equation. In both of these analyses, it was assumed that the 155 mm M107 projectile strikes normal to the ground surface at a velocity of 2244 feet per second. The calculated depths are greater than the recovery depths except for the 2.36" rocket.

Table 6: Penetration Depths in Sand Using Hydrocode Analysis and WES Equation

Ordnance Item	Depth using Hydrocode Analysis (ft)	Depth using WES Equation (ft)	Percent Difference Between Calculated Results
155 mm M107	16.8	14.0	16.7
105 mm M1	9.4	7.7	18.1
75 mm M48	5.7	4.9	14.0
40 mm	2.9	3.2	10.3
37 mm M63	4.1	3.9	4.9
2.36" Rocket	0.46	0.4	13.0

A PENCVR3D analysis assuming that the ordnance item strikes at an angle of 30 degrees from the ground surface at a velocity of 705 feet per second returns a maximum depth of penetration into sand of 3 feet. A hydrocode analysis of this case yields a penetration depth of 1.5 feet (see Figures 6 and 7). Examination of the recovery depths of 155 mm projectiles (see Table 6) shows that the recovered 155 mm projectiles were located at depths varying between 0.3 feet and 3.0 feet. Keeping in mind that the recovery depth may not correspond to the depth of penetration, it is not possible at this time to assess which analysis, PENCVR3D or hydrocode, yields the correct solution.

COMPARISON OF REQUIRED INPUT DATA

The WES equation requires three items of input data: ordnance weight, ordnance striking velocity, and soil penetrability constant. If there is any information available on the ordnance

item, the weight is included in this information. In this analysis, the striking velocity is assumed to be the muzzle velocity. This information is sometimes more difficult to obtain than the weight but it is usually available. The soil penetrability constants are listed in Table 1.

The hydrocode analysis requires more information than the WES equation. The geometry of the ordnance item is required. This includes the shape, the length, and the diameter. Ideally, a detailed production drawing of the item should be used. Such drawings can be difficult to obtain. Equations of state are needed for both the ordnance material and the soil. There are equations of state available for most common materials and soil from hydrocode experts if the appropriate ones are not included with the software utilized. The striking velocity and angle must be defined. In absence of any other information about this data, muzzle velocity and an angle normal to the surface will produce the most conservative (deepest) penetration depths.

The input required for the PENCVR3D analysis is similar to that required by the hydrocode analysis. A detailed production drawing of the item is essential in order to calculate the center of gravity of the ordnance item. Angle of entry and striking velocity must be defined. Again, muzzle velocity and an angle normal to the surface may be used to produce conservative results. A soil penetrability index must be defined. There is a table of typical values of this index included in the PENCVR3D users' manual.

Of these three analysis methods, the WES equation requires the least input data. This input data is also the most readily available data. The hydrocode analysis and the PENCVR3D analysis require comparable input data. Frequently, especially for the older ordnance items no longer in service, the data required by the hydrocode analysis and the PENCVR3D analysis are not available.

COMPARISON OF TIME AND EXPERTISE REQUIRED FOR ANALYSIS

The WES equation takes minimal time and expertise to use. The time required is directly related to the availability of data. Also, the only expertise required is that needed to obtain the data.

The hydrocode analysis requires a substantial amount of time and expertise. In addition to the time and expertise required to obtain the larger amounts of data, it takes both time and expertise to set up the hydrocode model. Computation time depends on several factors including hydrocode program used, size of model, computing efficiency of the computer used, and type of analysis (2D or 3D). Also to be considered is the cost of the software and the necessary computer if they are not already available.

The PENCVR3D analysis requires a larger amount of time and more expertise than the WES equation but less than the hydrocode analysis. The search for data requires the same amount of time and expertise as that required by the hydrocode analysis. Also, it is necessary to compute the center of gravity of the item from the production drawing if it is not available as a data item on the ordnance. This software is available to U.S. Government agencies and their contractors and NATO Government agencies from WES. It can be run on a personal computer under Windows 95 or Windows NT.

CONCLUSIONS

Several methods for calculating ordnance penetration into the ground have been discussed. On OE sites there are several unknowns that will affect the ordnance penetration: relative location of firing point and striking point (distance and elevation), topography between firing point and striking point at time of firing, propellant charge used, and soil condition (wet or dry). Also, since OE sites often have older munitions that are no longer in service, it can be difficult to obtain information about the munition (geometry, location of center of gravity, etc.).

The goal in calculating a penetration depth is to determine the maximum depth at which the ordnance item might expect to be recovered. The WES equation yields a conservative penetration depth and requires the least amount of data, time and expertise. Therefore, this calculation method should be used first.

If a more detailed analysis is desired then PENCVR3D or a hydrocode analysis may be used. However, it should be noted that there is not much to be gained by using one of these analysis method unless a trajectory analysis is performed to determine striking velocity and angle.

As more data is entered into the database minimum, maximum and average recovery depths can be found. However, this database doesn't tell what has happened to the munition between time of firing and time of recovery. For example, has soil been added or removed above the item and how much has frost heave affected the item? This database provides good historical data and may be used in the future to predict a range of depths at which an item might expect to be recovered.

REFERENCES

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5. Grant, D.E. and Crull, M.M., "Evaluation of PENCVR3D for Determination of Ordnance Ground Penetration," UXO Forum 99, Atlanta, GA, May 1999.
6. Adams, J.B., "Ordnance and Explosives Recovery Depth," UXO Forum 99, Atlanta, GA, May 1999.

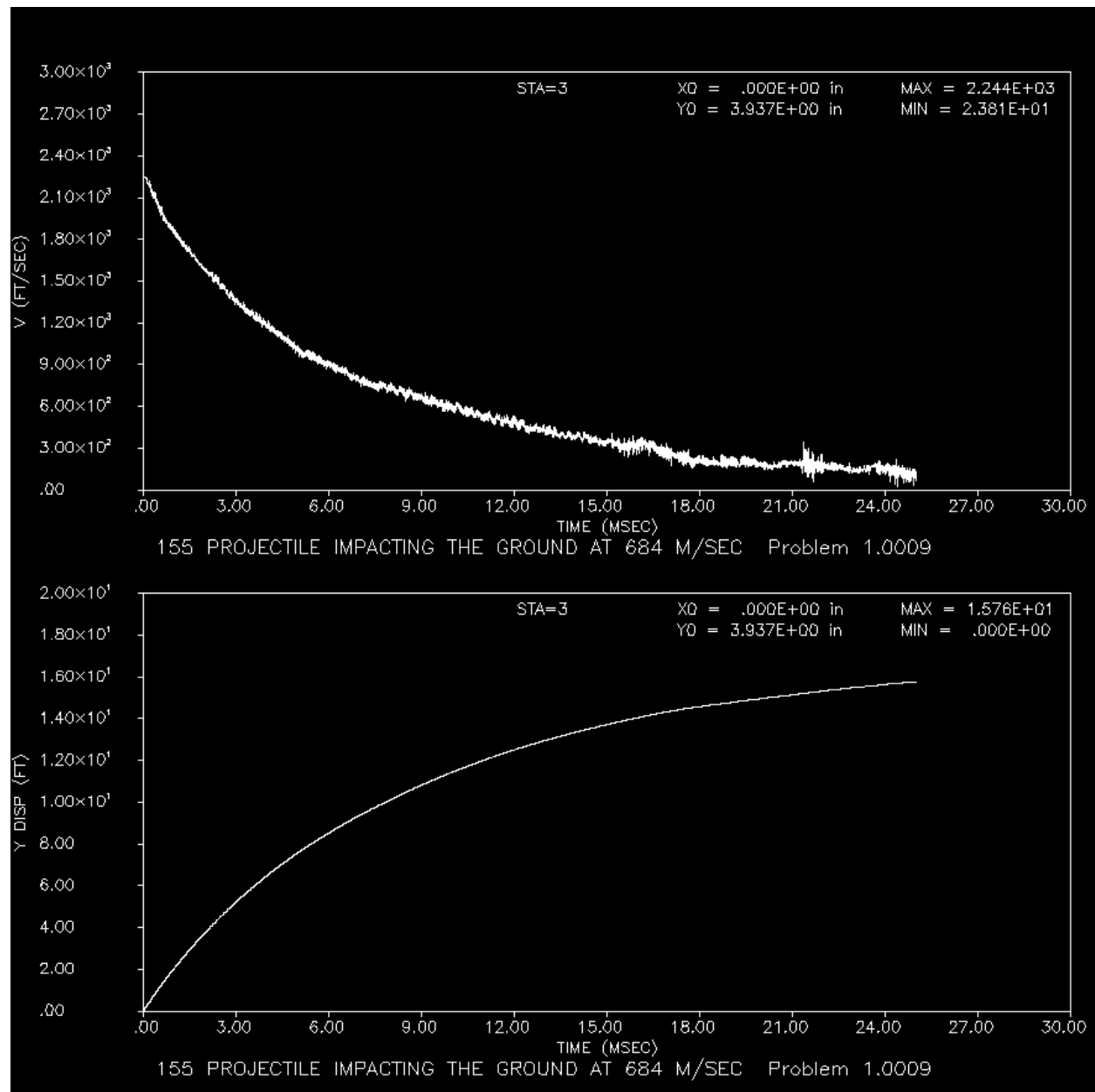


Figure 1. Variation of Velocity and Depth with Time for 155 mm M107 Impacting Sand

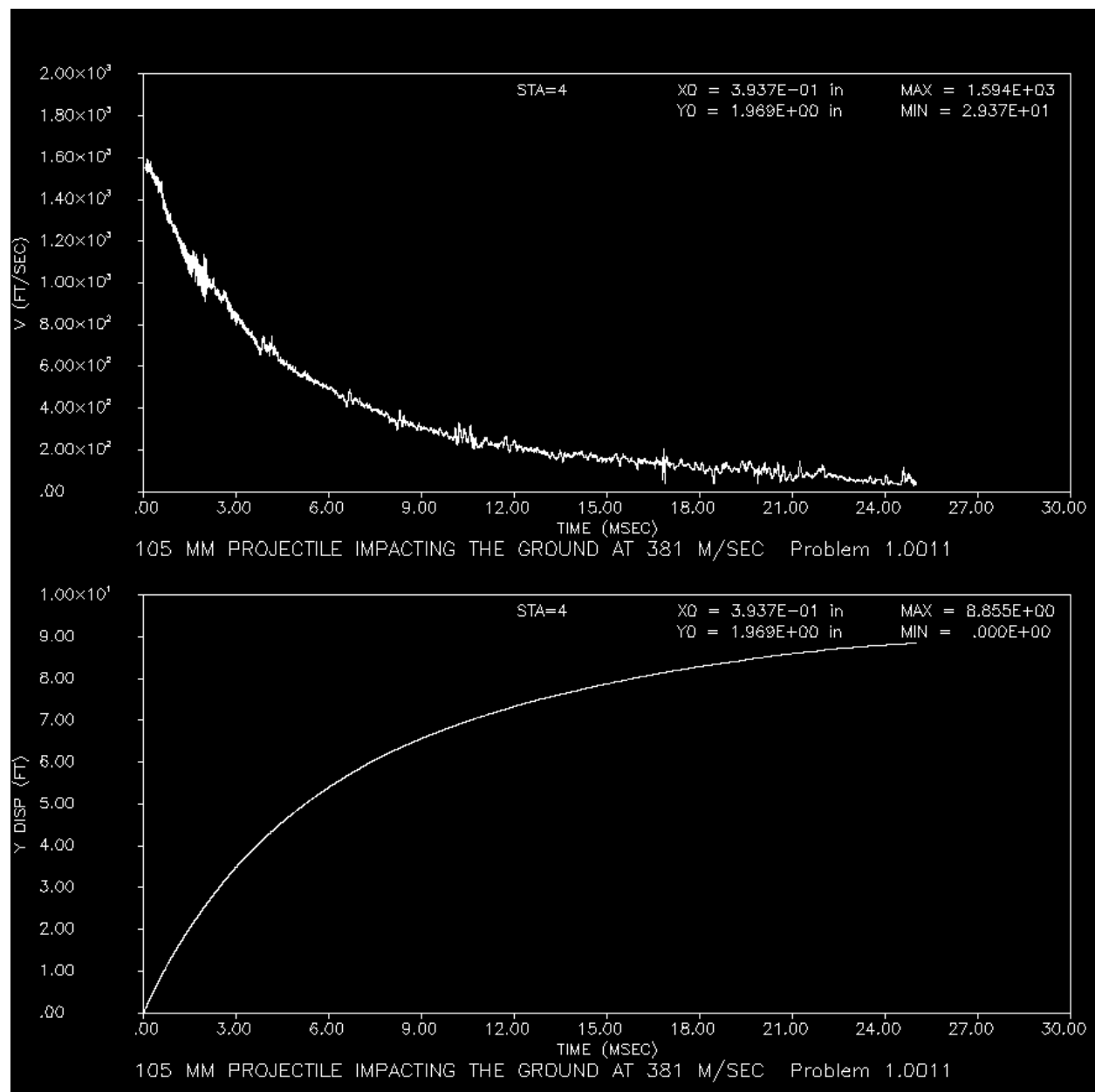


Figure 2. Variation of Velocity and Depth with Time for 105 mm M1 Impacting Sand

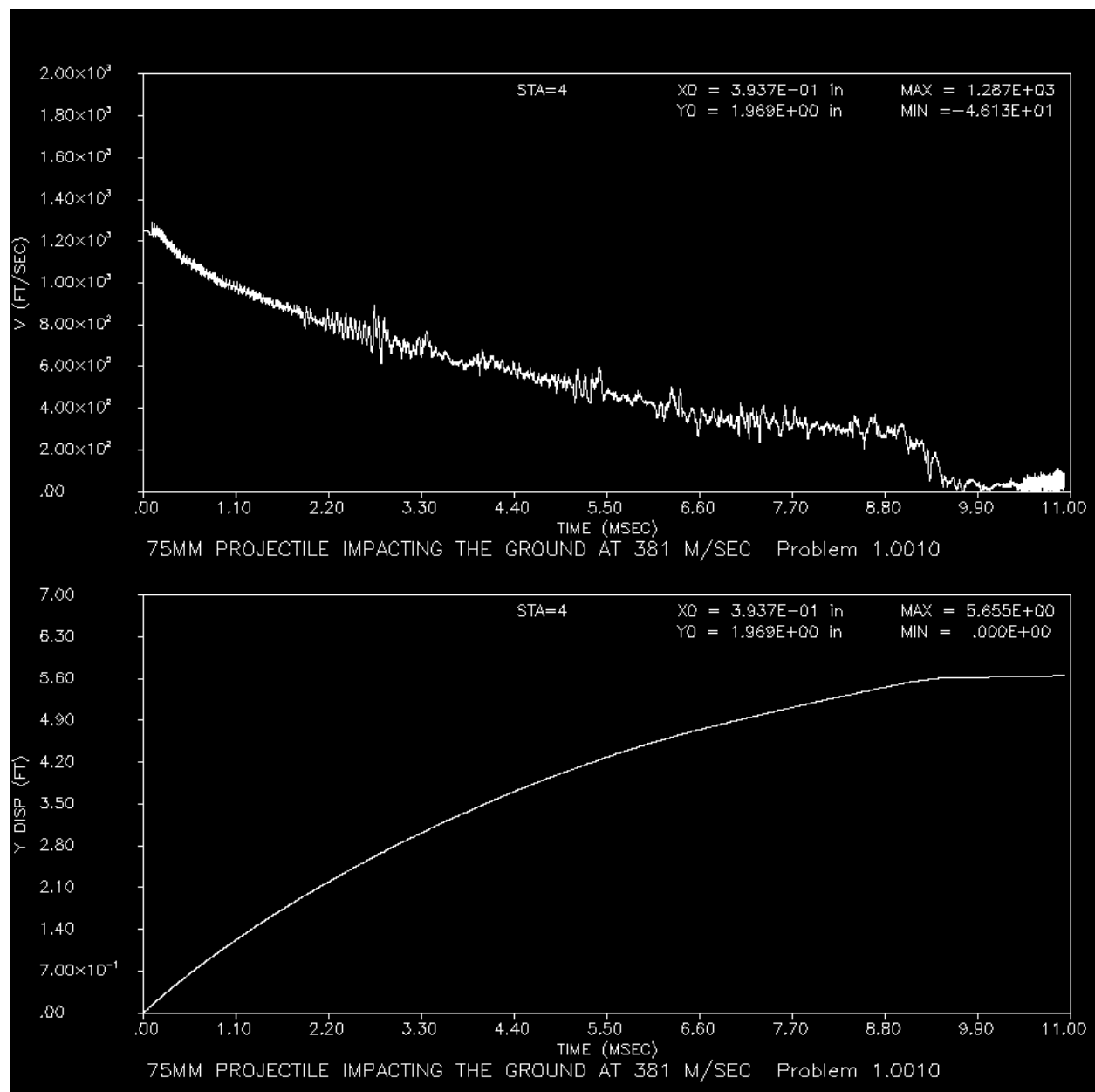


Figure 3. Variation of Velocity and Depth with Time for 75 mm M48 Impacting Sand

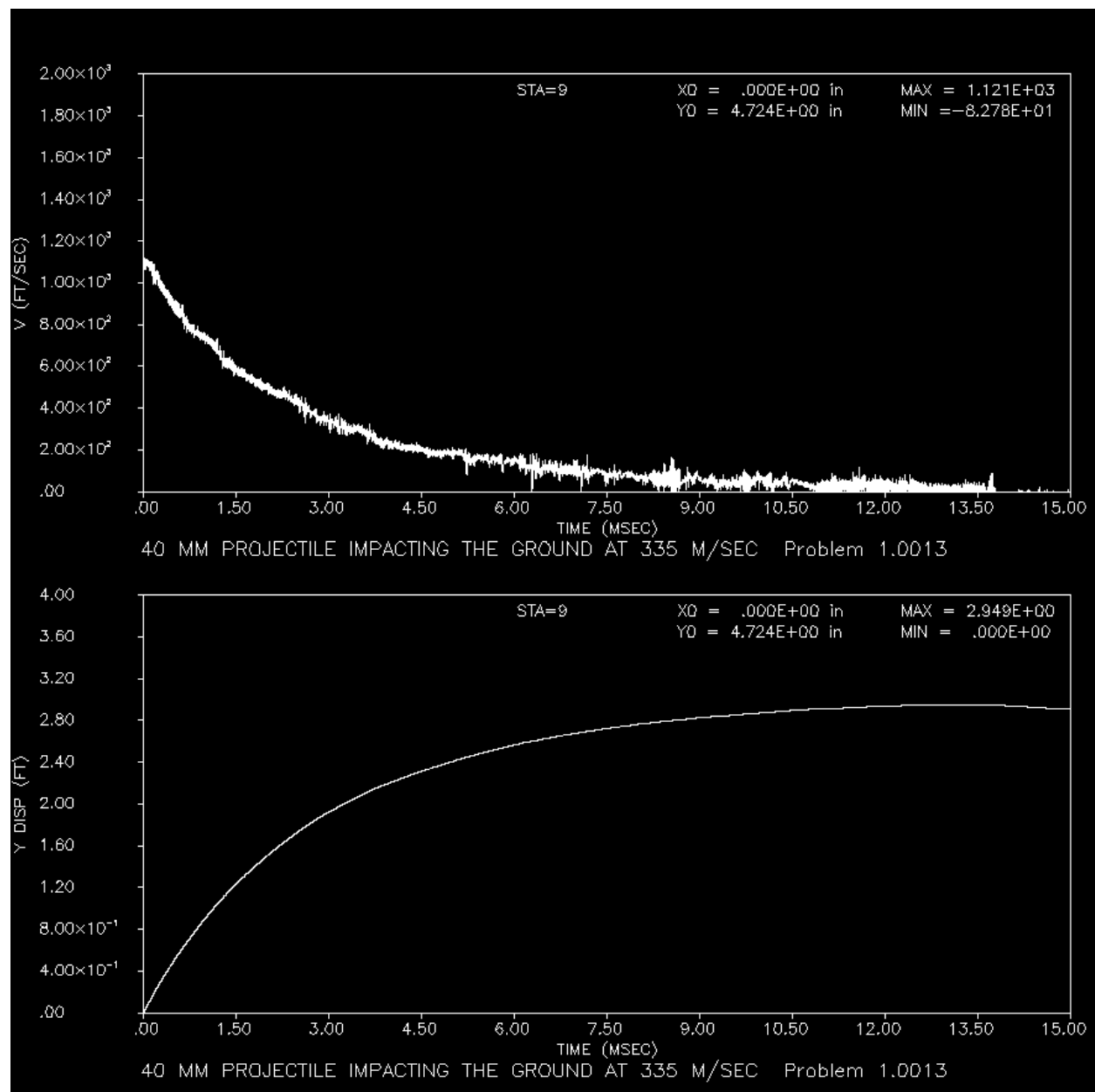


Figure 4. Variation of Velocity and Depth with Time for 40 mm M822 Impacting Sand

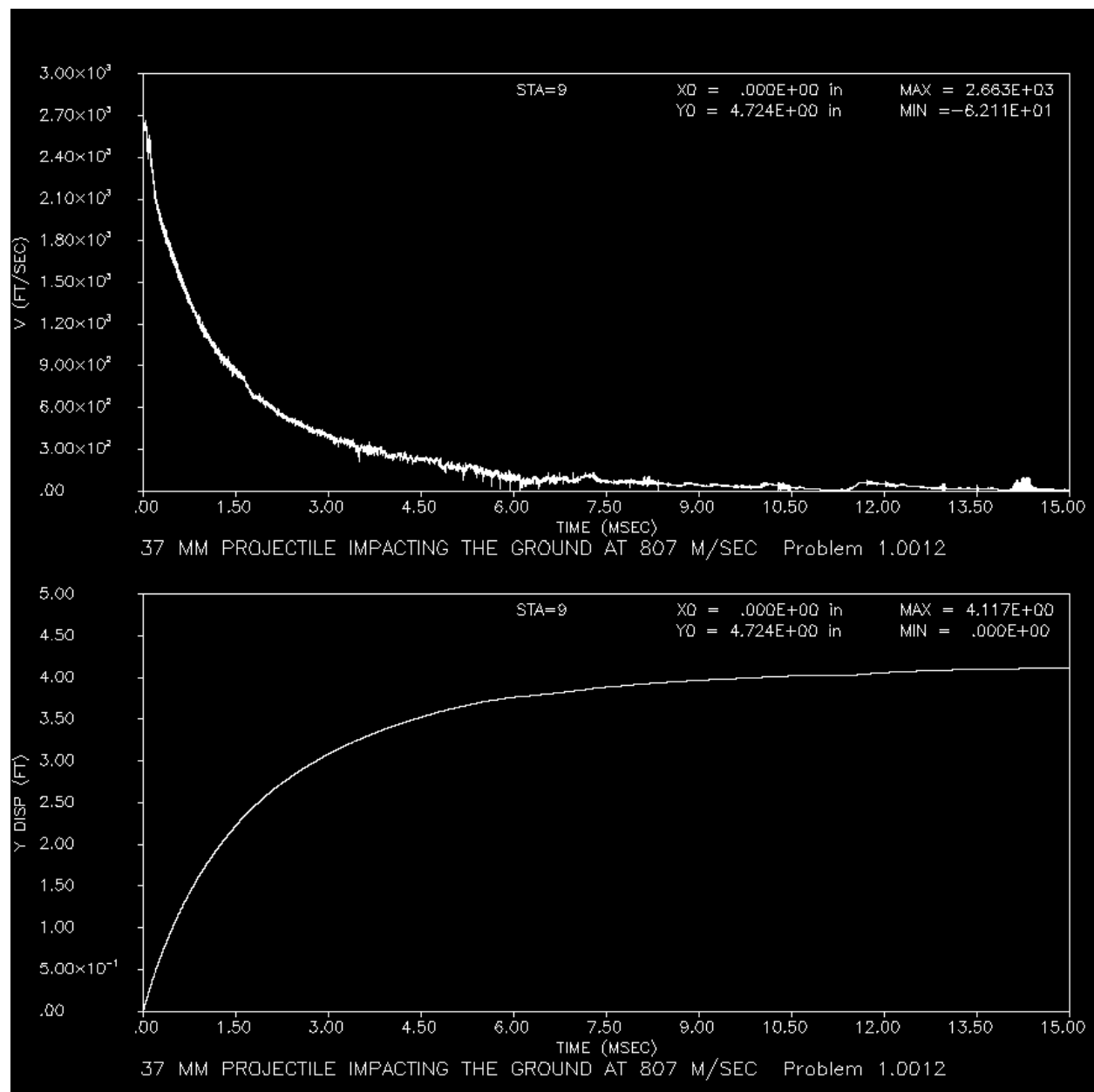


Figure 5. Variation of Velocity and Depth with Time for 37 mm M63 Impacting Sand

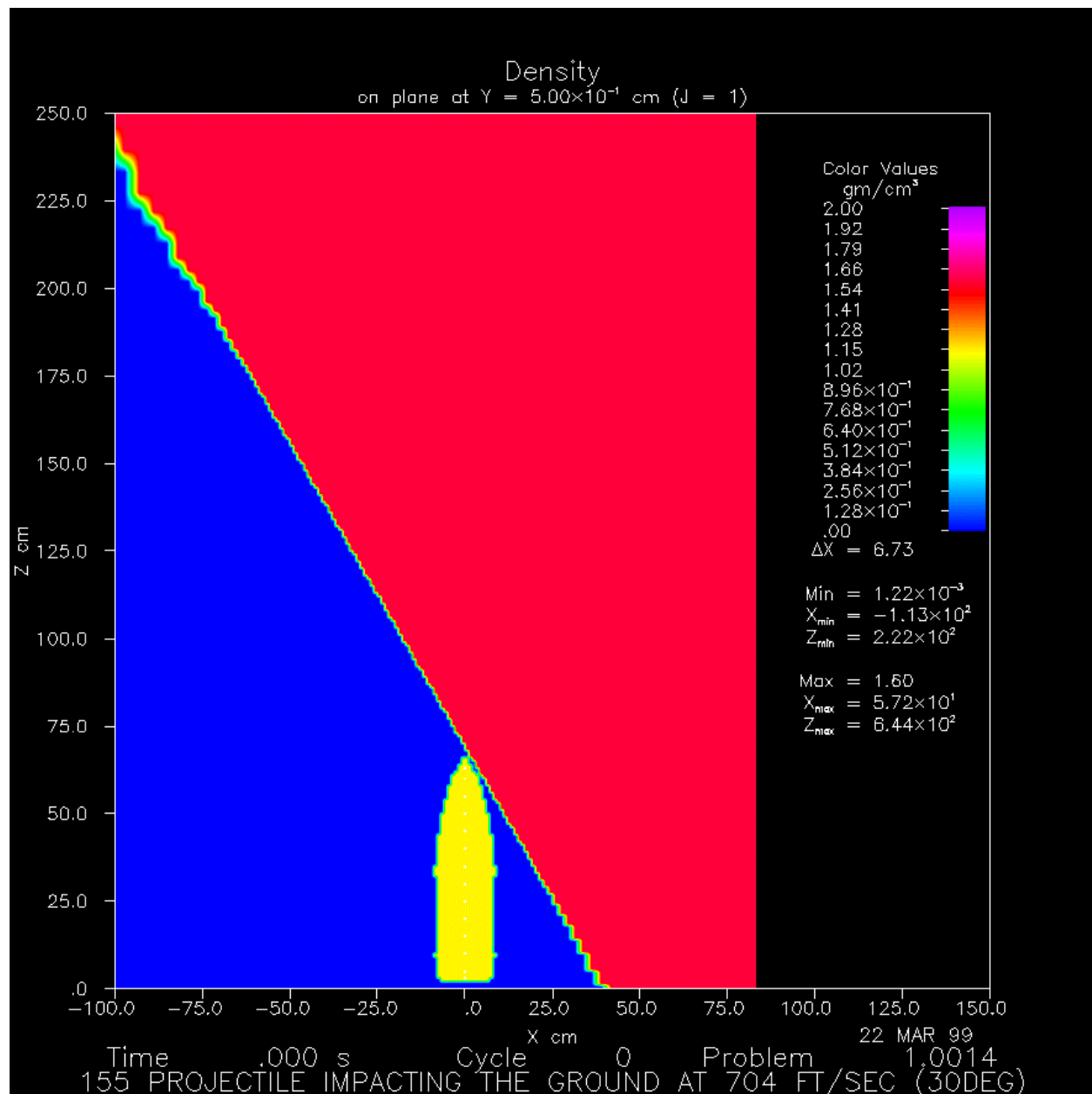


Figure 6. Hydrocode Model of 155 mm M107 Impacting Ground at 30 degrees at 704 ft/sec

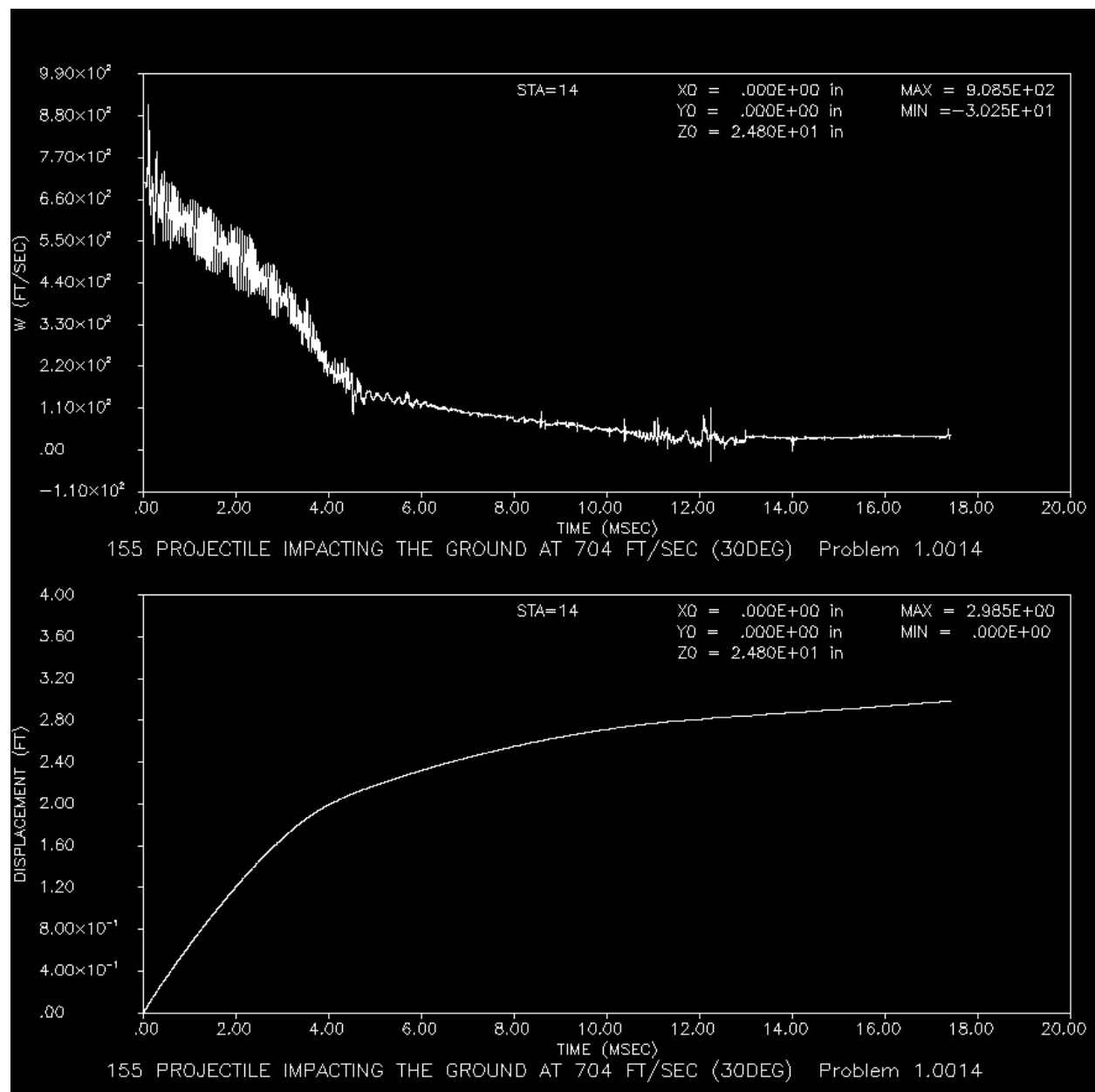


Figure 7. Variation of Velocity and Depth with Time for 155 mm M107 Impacting Sand at 30 degrees at 704 ft/sec